DoD "State of the Art" in IR Detection, Future Needs and Current Status
&
GaInSb/InAs Superlattice Materials for Detectors

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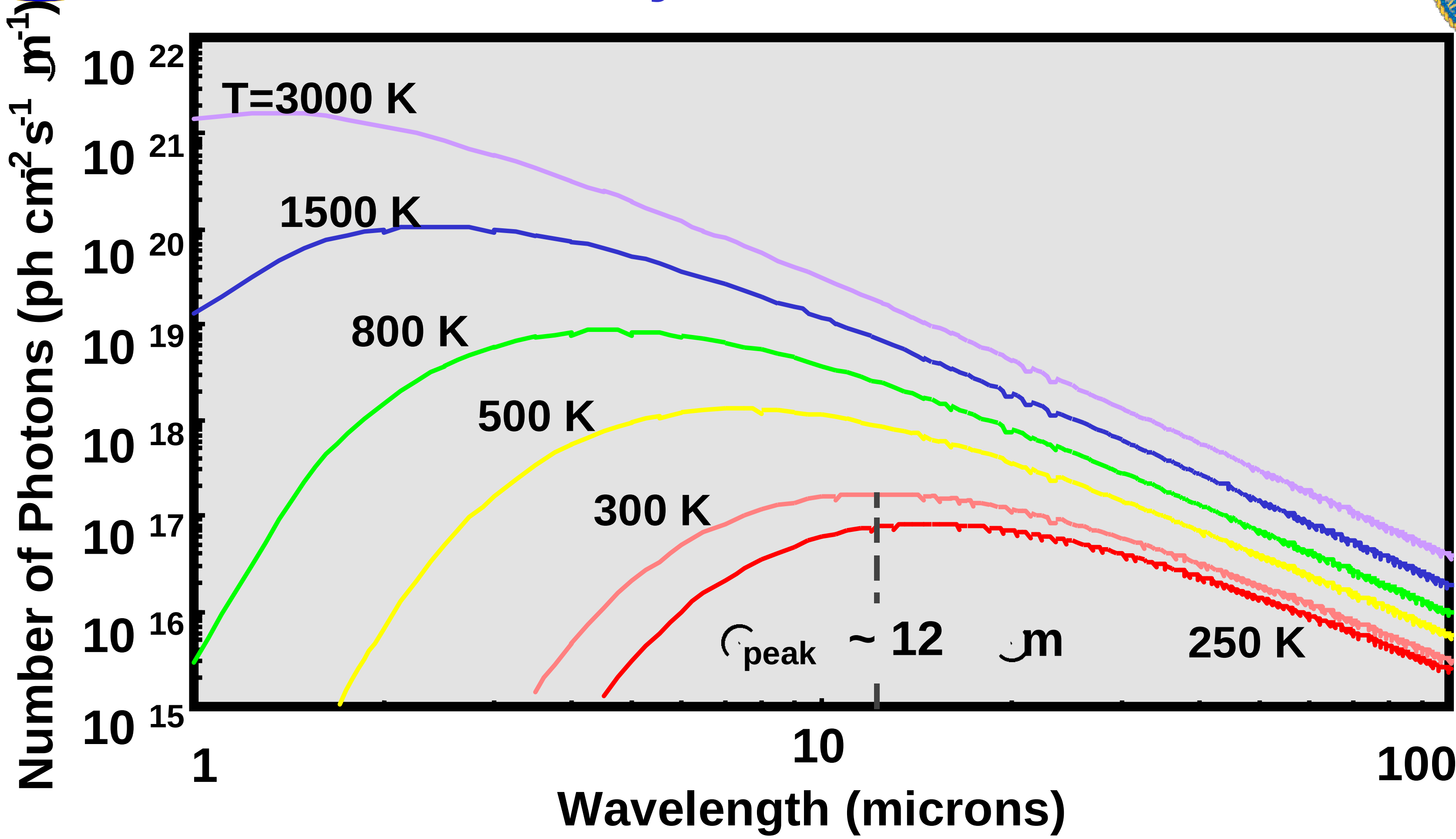
Presentation Outline

- Military Infrared Sensors
- IR Sensing Fundamentals
- IR detector / FPA fundamentals
- Current IR technology status
- Emerging technologies and future needs
- GaInSb/InAs superlattice detector materials
    - Current status
    - Materials/device research issues
    - Applications

Navy Infrared Systems

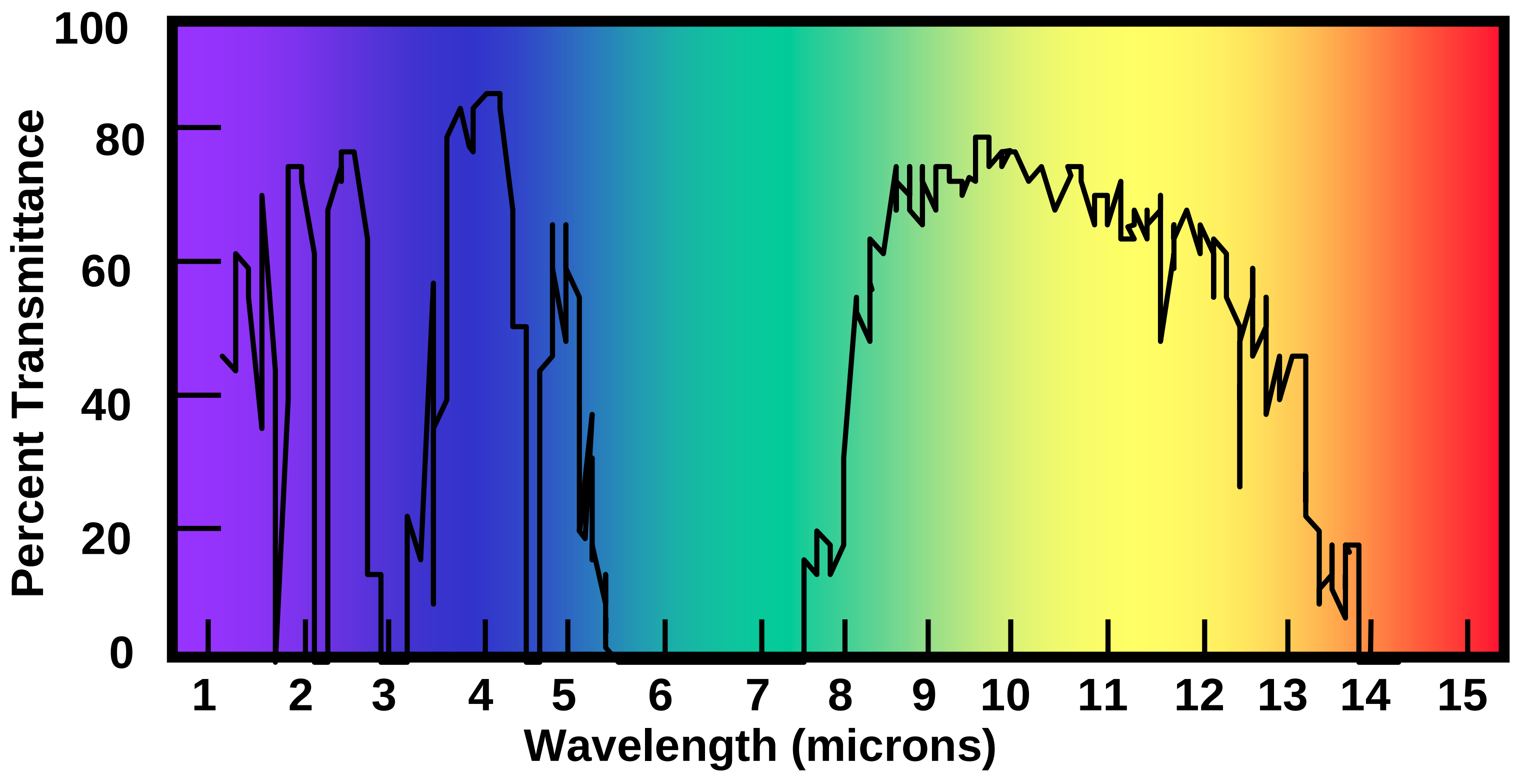
- **Active systems**
  - **LIDAR(Laser Infrared RADAR)**
- **Passive Systems**
  - **FLIRs (Forward Looking Infrared)**
    - **Imagers for navigation, target acquisition, fire control, reconnaissance**
      - **Fixed wing and rotary aircraft, ships, armored vehicles, manportable**
  - **Seekers**
    - **Imaging and non-imaging for missile guidance**
      - **Tactical and strategic, A-A, SA, A-S**
  - **Airborne threat warning sensors**
    - **Imaging with autonomous processor for fighter and transport aircraft**
  - **IRSTs (Infrared Search and Track)**
    - **Non-imaging tactical aircraft and shipboard**

Blackbody Emission Curves



• All objects emit electromagnetic radiation as a result of the thermal excitation of atoms. As the object's temperature increases, the intensity of the radiation increases and the peak of emission moves to shorter wavelengths. This radiation is the basis for night time passive infrared imaging sensors.

IR Transmittance of 1 km Path at Sea Level



- The atmosphere has two regions of transparency in the infrared portion of the electromagnetic spectrum where there is sufficient self-emitted radiation from near ambient temperature objects for passive imaging. These ‘windows’ occur between 3-5 (MWIR) and 8-14 μm (LWIR).
- For exoatmospheric applications where this is no absorption, longer wavelengths (e.g. 18-30 μm, VLWIR) offer improved sensitivity for low temperature targets.

IR Detector Types

- Thermal detectors
    - Photons converted into phonons (heat) which change some physical property
        - Bolometric (resistance), pyroelectric (spontaneous polarization)
    - Typically operate at or near room temperature with modest sensitivity, but available at low cost.

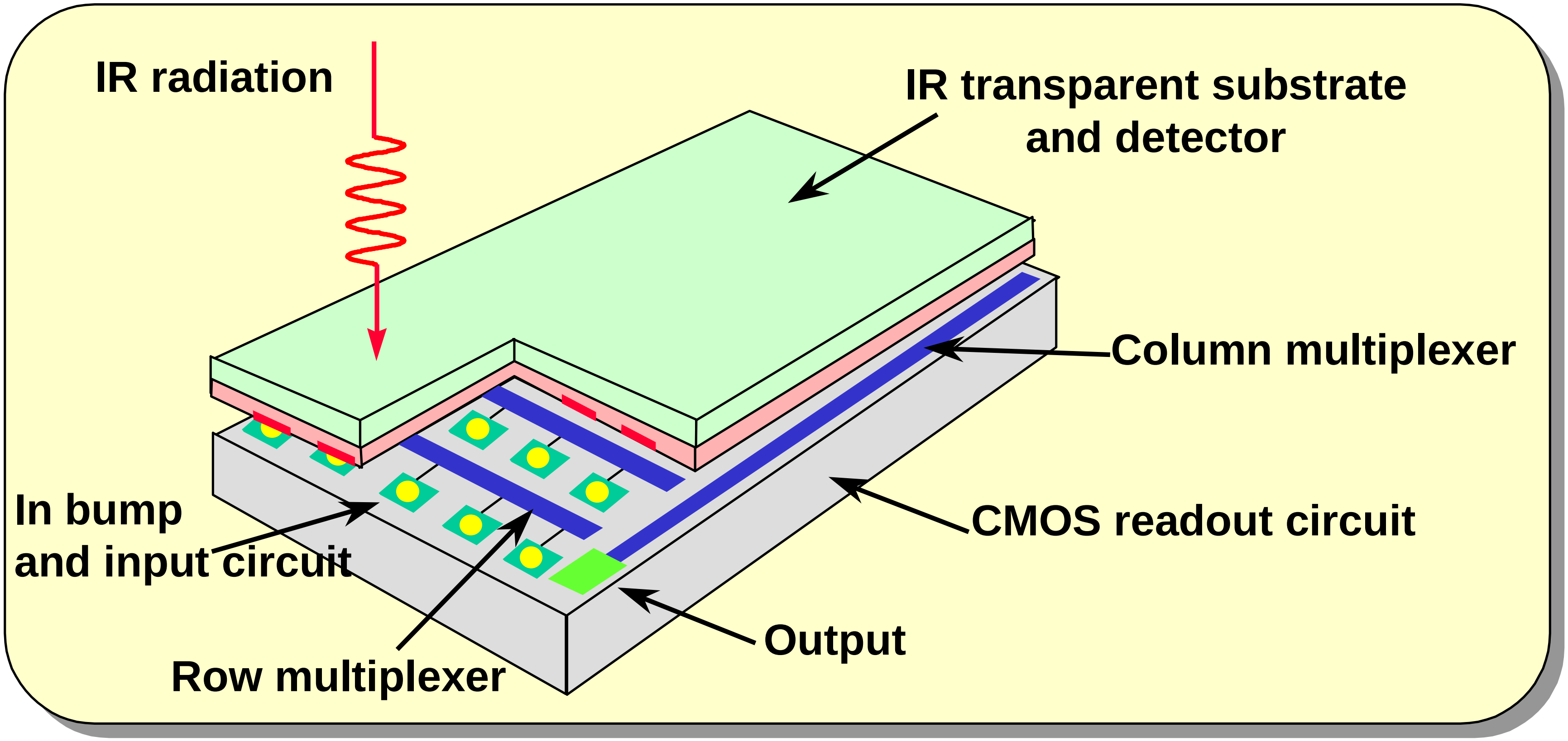
- Photon detectors
    - Photons converted into electrons(holes) which are sensed directly as a current or charge
        - Photoconductor or photovoltaic (junction) semiconductor device.
    - Typically operate at cryogenic temperatures (4 - 200K) with high sensitivity, but with at higher cost.

Military IR Detector Technology Historical Evolution

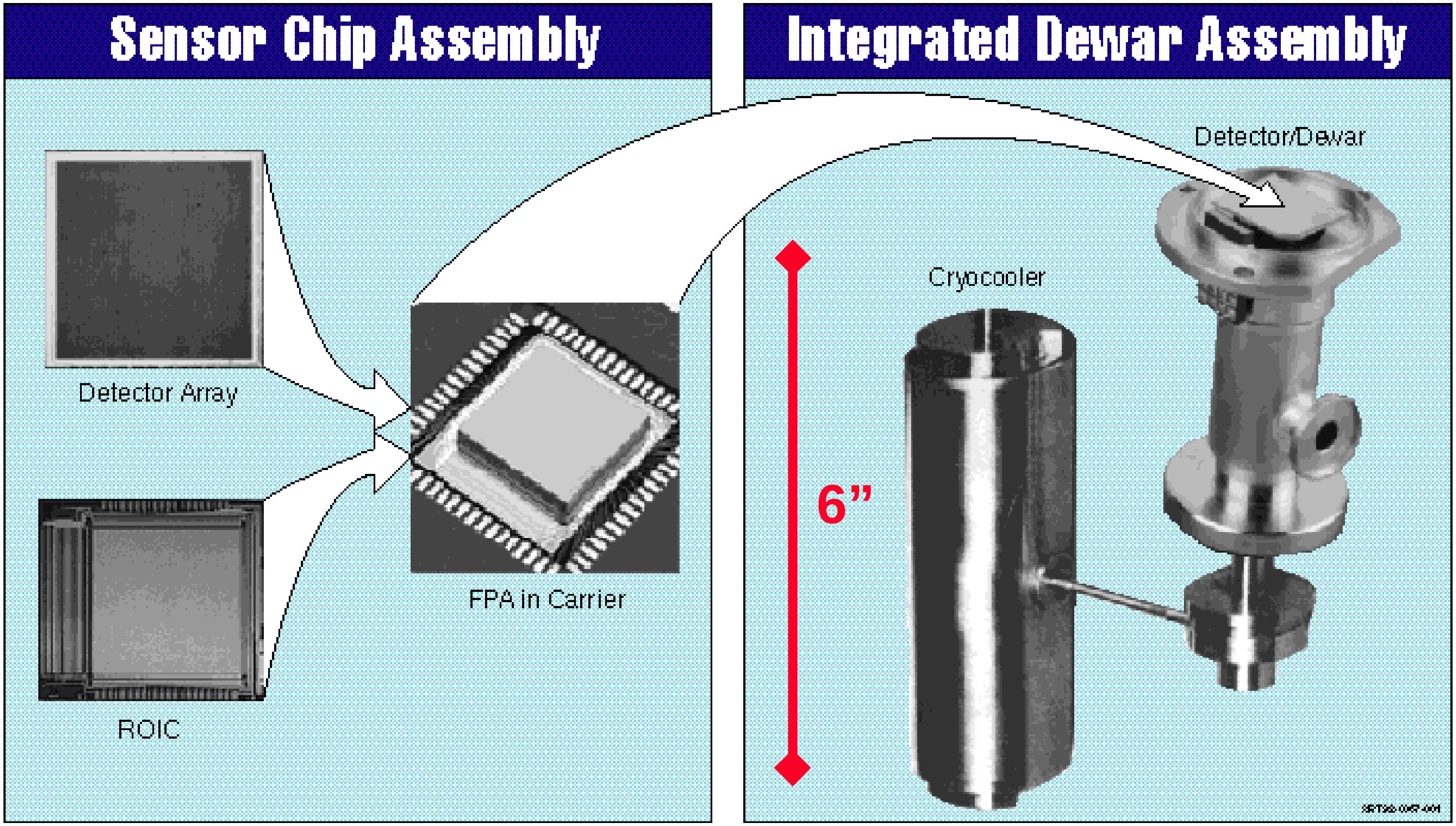
- Single detector element scanned over 2 dimensions to cover scene. (Obsolete)
- Linear arrangement of detectors scanned in one dimension to cover scene. (Workhorse for past 20 years)
- “Two dimensional” array (e.g. 480x4) of detectors, with TDI (time delay and integration) for enhanced sensitivity, scanned in one dimension to cover scene. (Implemented over past 5 years)
- Two dimensional array (e.g.. 480x640) of detectors ‘staring’ at the scene. (Emerging technology, first arrays just now in systems).
- Multi-Spectral staring array technology (Currently in development, available at high cost in small numbers)

IRFPA (Infrared Focal Plane Array) Architecture

- 2 dimensional infrared detector array electrically and physically mated to a Si ROIC (read-out integrated circuit)

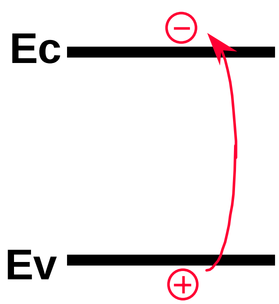


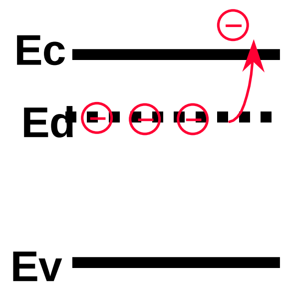
Typical IRFPA Sub-Assembly

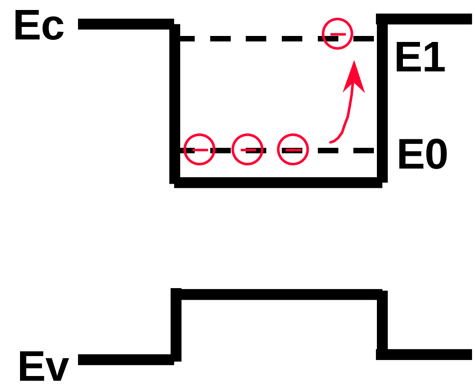


- Detector & ROIC
- Minature cryocooler and dewar assembly

Semiconductor Infrared Detection Mechanisms







- Intrinsic
- Interband
- InSb, HgCdTe, III-V superlattices
- Established approach for 'tactical' applications
- High performance moderate cooling requirement

- Extrinsic
- Impurity level
- Si:Ga, Si:As, Ge:Hg
- Established approach for VLWIR strategic applications
- High performance, low operating temp

- Quantum Well
- Inter-subband
- AlGaAs/GaAs, Si/SiGe
- Lower temperature required than intrinsic detectors
- Potential to leverage III-V tech base to achieve low cost.

IRFPA Performance Considerations

- **A high performance IRFPA should convert the available photon flux (typically f/2 optical system) into an electrical signal without introducing any noise greater than that caused by the random fluctuations in arrival rate of background photons, (BLIP, Background Limited Performance) with low power consumption at the highest possible operating temperature**

  - **Si ROIC requirements: Low noise(<200 μV, high charge capacity > 10^8 cariers**

  - **Detector requirements:**

  - **Large signal levels**
    - **High quantum efficiency across spectral band (>80%)**
    - **High responsivity (Signal >> ROIC noise level).**
  - **Low noise levels**
    - **Low dark currents, << 1 mA/cm^2 (8-10 μm spectral band)**
  - **Good linearity (>99.9%)**
  - **Adequate temporal response (τ~μsec)**

IR Detector Performance Parameters

- ***Detectivity*** D* (cm-Hz$^{1/2}$/Watt) - Signal to noise ratio normalized to detector area

  $D^* = R / I_n^* \text{ Area}^{1/2}$ (Maximize responsivity and minimize noise)

- ***Responsivity*** R(amps/Watt) - Electrical sensitivity of detector for conversion of photon flux to current

  • High responsivity requires high absorption and efficient collection of photogenerated carriers.

  - Large absorption coefficient, adequate material thickness (several microns), good mobility (>1000 cm^2/V-s), good lifetime (>1μsec)

- ***Noise spectral density*** I_n(amp/Hz $^{1/2}$) - Electrical noise current in the detector across the detector bandwidth

  •$I_n \propto (I_{photon} + I_{dark})^{1/2}$ Want $I_{dark} << I_{photon}$ to minimize noise and achieve background photon limited performance (BLIP).

  - For narrow bandgap semiconductors diffusion of thermally generated minority carriers is the intrinsic limiting dark current mechanism at elevated temperatures. For a one sided abrupt p+/n junction: $I_{dark} \propto e^{(-Eg/kT)}(kT\mu/\tau)^{1/2}/Nd$.

    Maximize τ at large Nd to minimize dark current noise

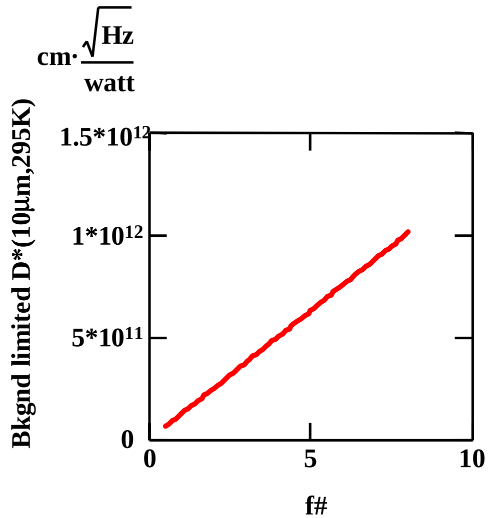
  - Material defects often keep one from reaching this limit

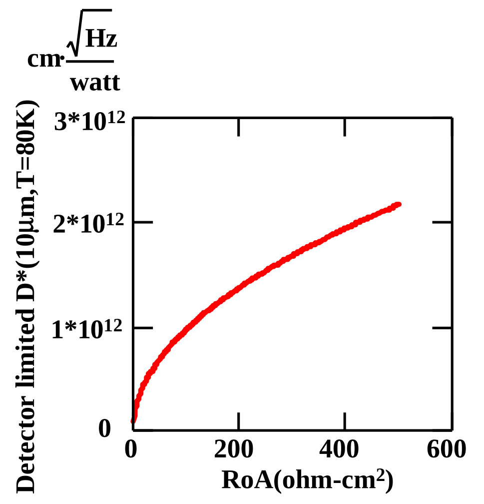
    Shockley-Read depletion layer generation currents

    Defect assisted tunneling currents

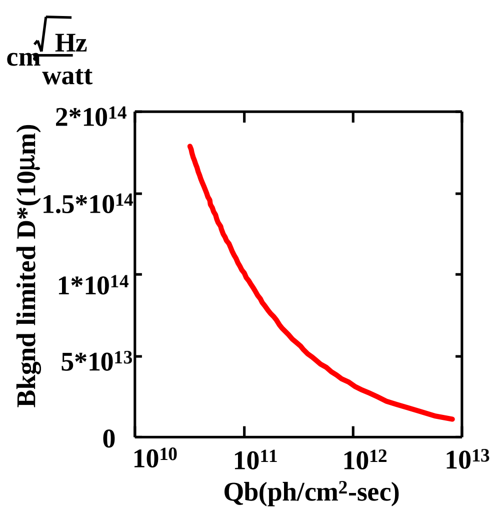
    - Minimize defect related states in the gap, and macroscopic defects that cause excess dark current

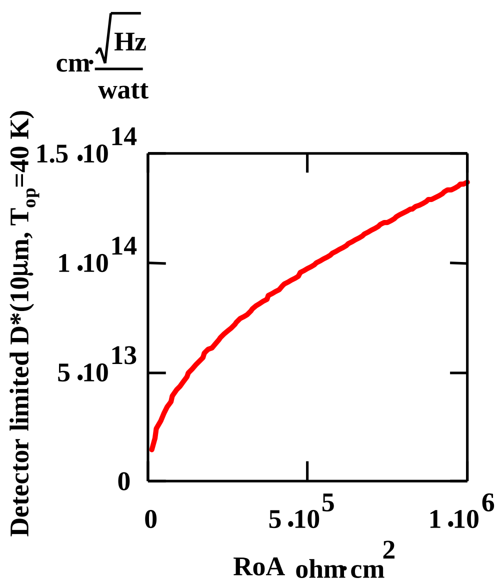
D* and RoA Requirements for Tactical and Strategic Backgrounds





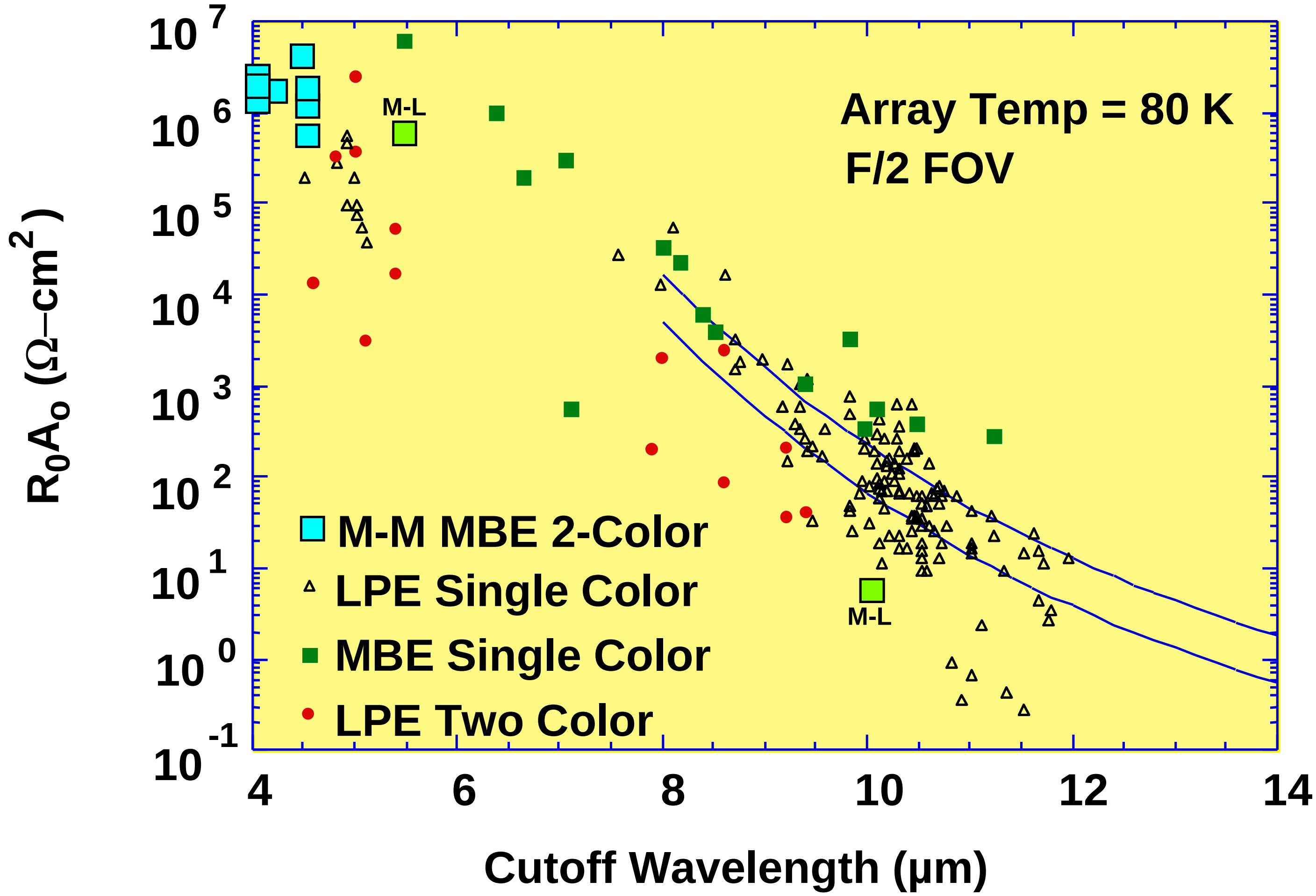
- For slower optics, higher quality detectors are required to achieve BLIP even for tactical applications.
  - RoA ~ 500 Ω–cm^2





- For the low backgrounds typically found in strategic applications, very high performance detectors are required to achieve BLIP.
  - RoA ~ 5*10^5 Ω–cm^2

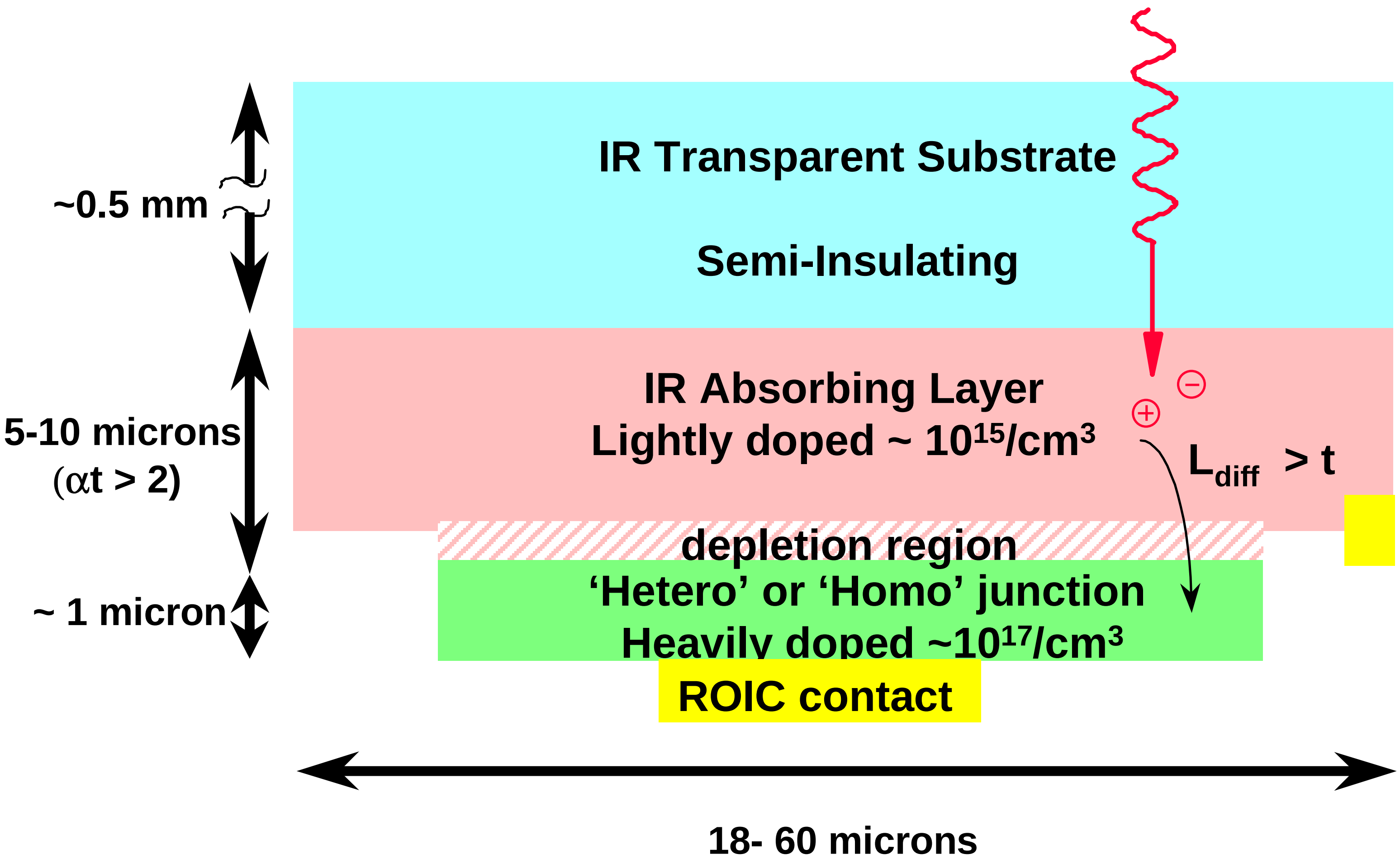
HgCdTe PV Detector "Trend Line' Performance



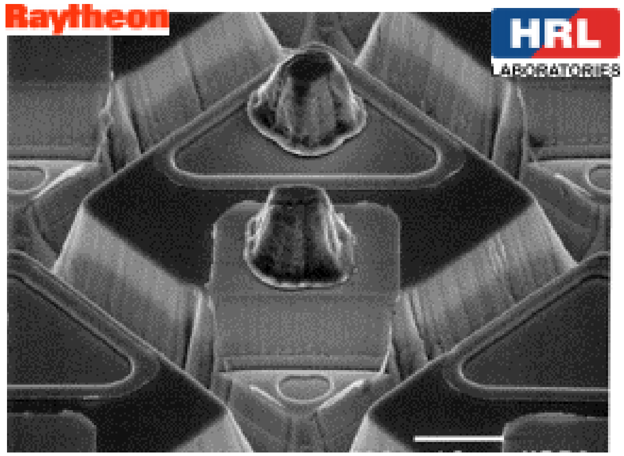
Current LW/VLW IRFPA Technology Status

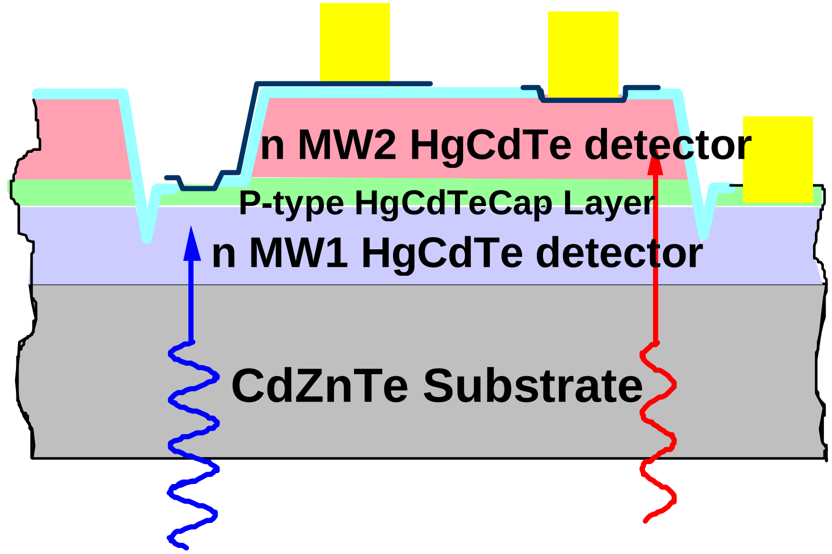
Detector Type/ Material	Cutoff Wavelength (microns)	Operating Temp (K)	Array Format	Peak D* (Jones)
PV HgCdTe	10	80	640x480	$1*10^{11}$
PV HgCdTe	10	80	256x256(R)	$4*10^{11}$
PV HgCdTe	11.5	78	128x128	$2*10^{11}$
EQWIP GaAs/ALGaAs	8.8	80	64x64(LV)	$5*10^{10}$
QWIP GaAs/AlGaAs	9.3	65	64x64(L)	$2*10^{10}$
QWIP GaAs/AlGaAs	9.7	78	64x64(LV)	$6*10^{9}$
QWIP GaAs/AlGaAs			480x640(L)	
PV HgCdTe	12.8	40	128x128	$1*10^{14}$
PV HgCdTe	14.3	60	128x128(R)	$3*10^{11}$
PV HgCdTe	15.8	40	128x128(R)	$1*10^{13}$
QWIP GaAs/AlGaAs	15	40	128x128	$1*10^{12}$
QWIP GaAs/AlGaAs	15	30	128x128	$1*10^{13}$

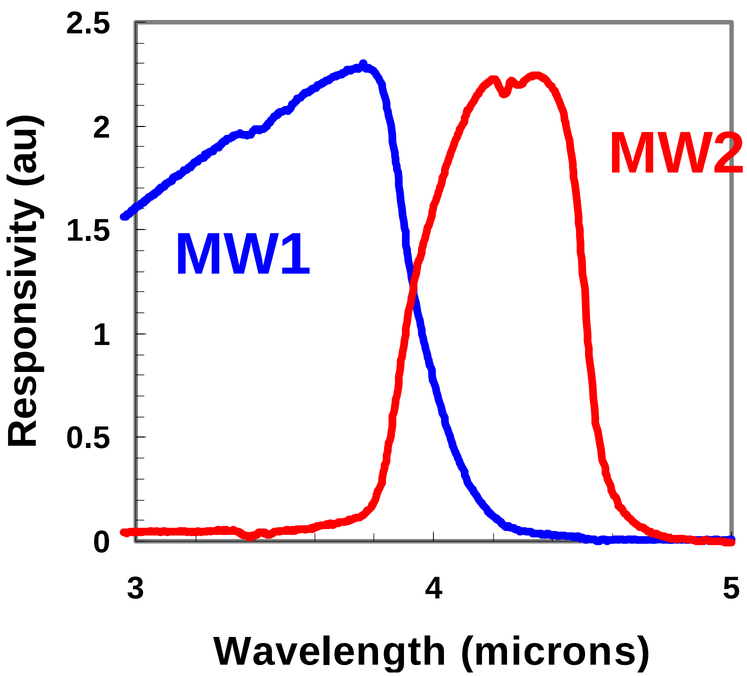
Typical Photovoltaic IR Detector



Two Color HgCdTe Infrared Detector





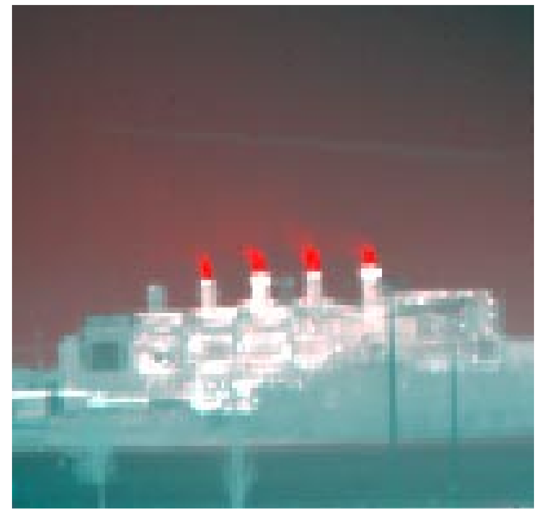


- MBE grown HgCdTe heterojunctions
- RIE detector delineation
- 128x128 40 micron pitch detectors
- 0.8 μm design rule commercial foundry CMOS ROIC
- Simultaneously integrating spatially colocated detectors
- No sacrifice in sensitivity over single color detectors

New and Emerging Needs in IRFPA Development

- Multispectral IRFPAs
  - MW-MW, MW-LW, LW-LW, MW-MW-LW, MW-LW-LW, LW-LW-LW, SW-MW-LW
- Higher operating temperature IRFPAs
  - > 120 K for LW
- Longer cutoff wavelength IRFPAs
  - Out to 18 microns for strategic applications
- Very large format IRFPAs
  - 5K x 5K for reconnaissance (10 cm x10 cm!!)

Spectral Discrimination of CO2 Emission From Blackbody Sources - 2 Midwave Bands



- **Commercial aircraft and coal fired power plant images showing power of current multispectral IRFPA technology for target discrimination**

Target-Decoy-Debris Discrimination for TMD & NMD

- Multispectral focal planes allow initial “bulk filtering” based on temperature determination, which eliminates many decoys and debris. LW bands required.
- Need at least 2 bands for temperature determination
- 2 Bands requires assumption of emissivity of 1 in both bands.
  - For reflective objects, earthshine or sunlight (if $< 5\ \mu m$ band used) results in errors in both temperature and area
- 3 Bands allows determination of emissivity (must assume object is gray body).
  - Rejects reflectivity induced errors.
- 4 Bands allows non-gray body assumption

Zero Contrast Problem, Tank-in-the-Woods - 3 LW Bands

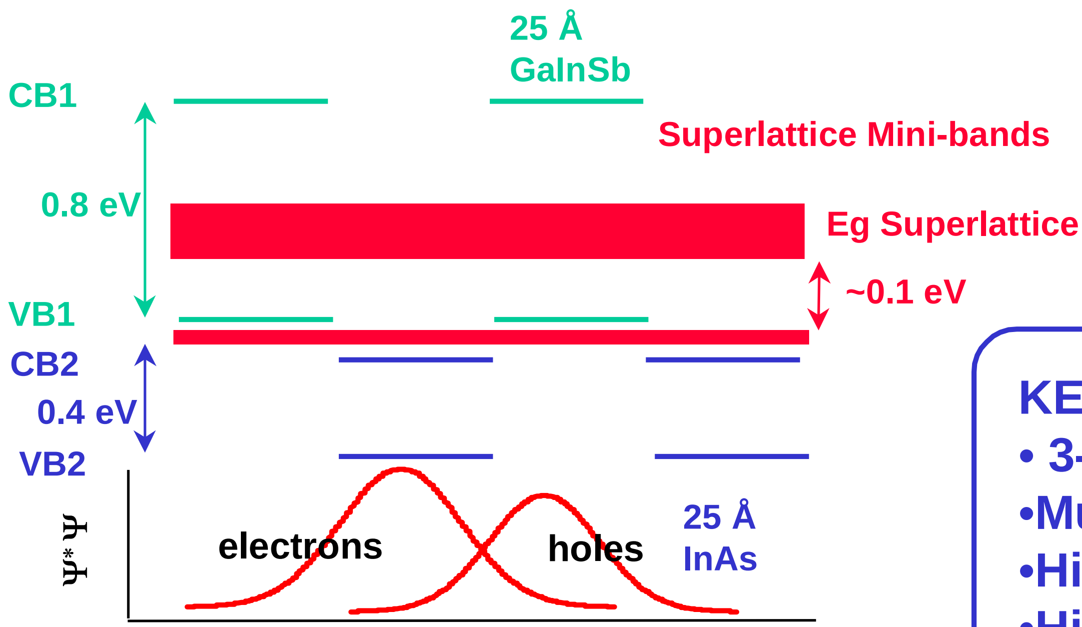
• LW single band image of tank at edge of woods at zero contrast.

• Three band (8-9, 9-10, 10-11 μm from filter wheel sensor) RGB image clearly showing tank as one of only a few red objects in scene.

• Multispectral IR provides target ID under conditions where a single band fails to show the target. Color display aids in object recognition

- Courtesy Dean Scribner, NRL 5636

GaInSb/InAs Superlattice Band Structure



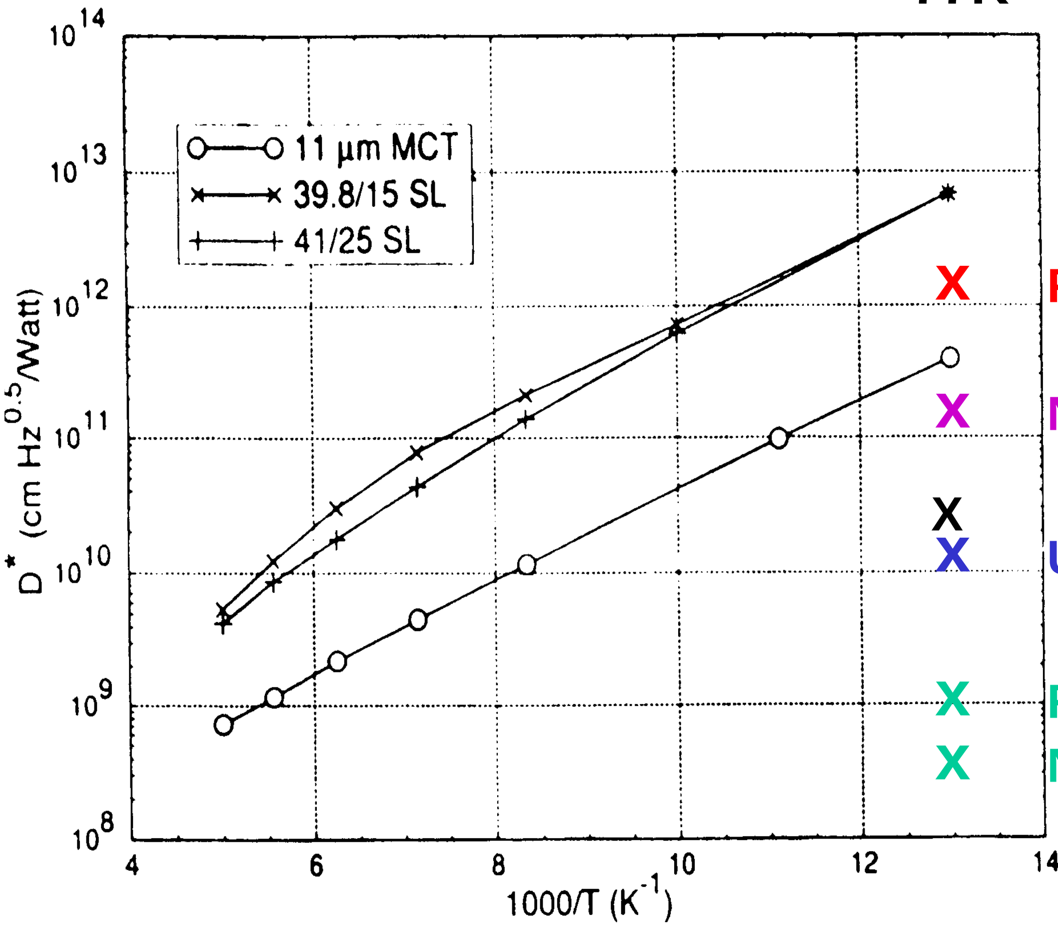
CB - Conduction band edge
VB - Valence band edge

KEY CAPABILITIES
- 3-18 micron cutoff
- Multispectral
- High quantum efficiency
- High operating temperature

- **Type II band alignment, GaInSb valence band above InAs conduction band**
  - **Quantum confinement and strain effects result in small bandgap semiconductor for layer thicknesses near 25 Å**
  - **Cutoff wavelength (I.e. bandgap) determined by layer thicknesses and strain, large wavefunction overlap yields large absorption coefficients**

Theoretical and Experimental Performance of Long Wavelength GaInSb/InAs Superlattice

77K



- Theoretical curves based on achieving intrinsic Auger lifetime at low temperatures and 11 µm

X Fuchs *et al.*, 1997 (8 µm)

X NRL, 1996 (8 µm)

X Fuchs et. al., 1997 (10 µm)

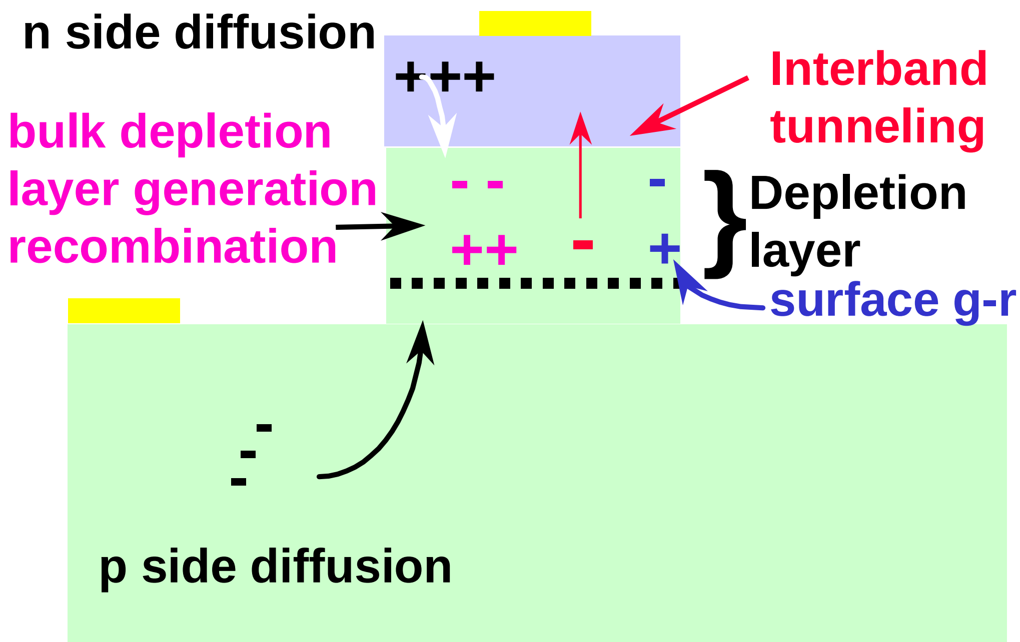
X UCSB/SBRC, 1993-96 (11 µm)

X Razeghi *et al.*, 1997 (10 µm)

X NRL, 1994 (8 µm)

GaAs substrates

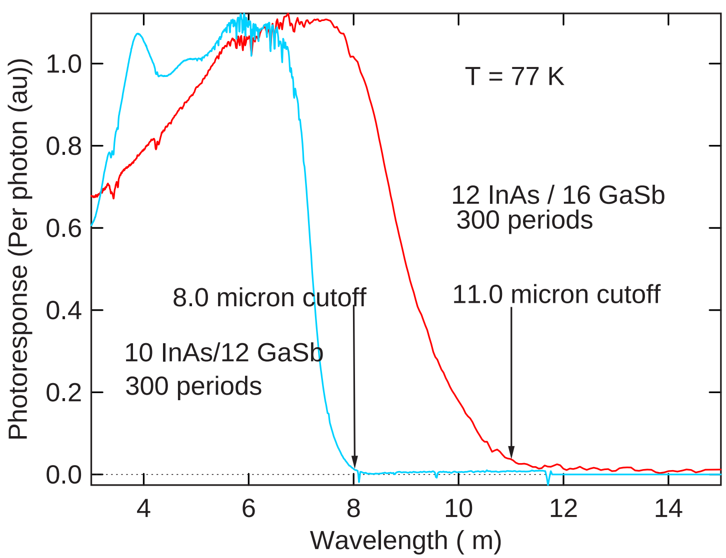
Diode Dark Current Sources

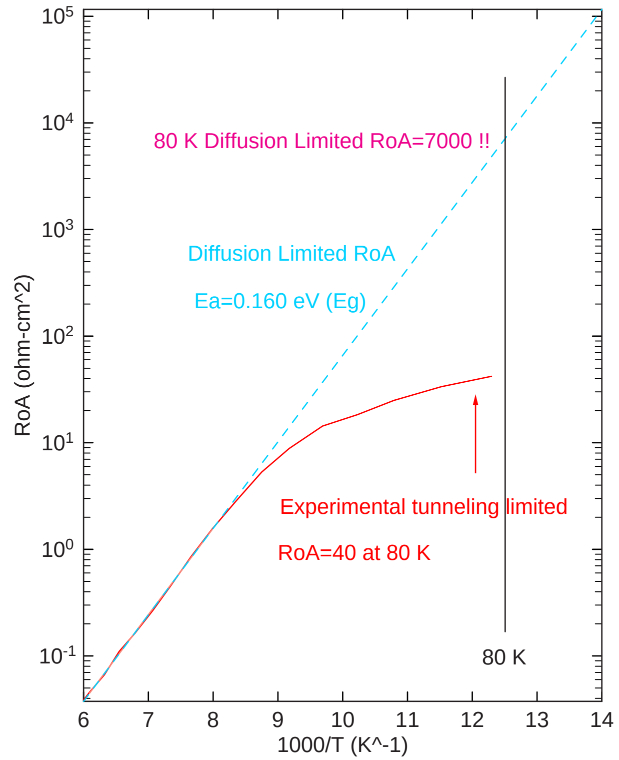


- Bias and temperature dependence
  - Diffusion current
    - $I(Vj)=Is_{diff}(e^{qVj/kT}-1)$
  - G-R current
    - $I(Vj)=Is_{gr}(e^{qVj/2kT}-1)$
- Diode figure of merit: RoA
  - Dynamic resistance at zero bias
    - $Ro=(dI/dV)_{Vj=0}^{-1}$
- Current density:
  - $J(Vj)=kT\ (RoA)^{-1}\ (e^{qVj/nkT}-1)$

•High RoA results in low dark current and low noise

GaInSb/InAs Superlattice IR Detector Characteristics





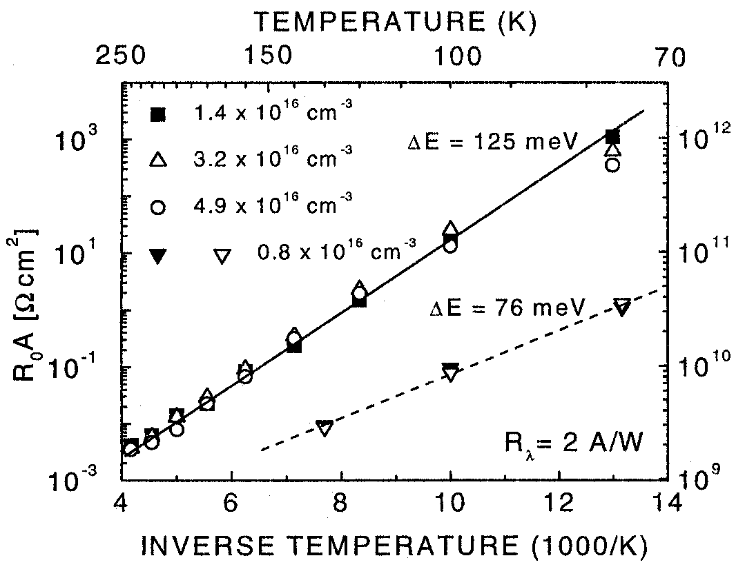
- **Long wavelength cutoffs in the 8-12 μm band demonstrated**

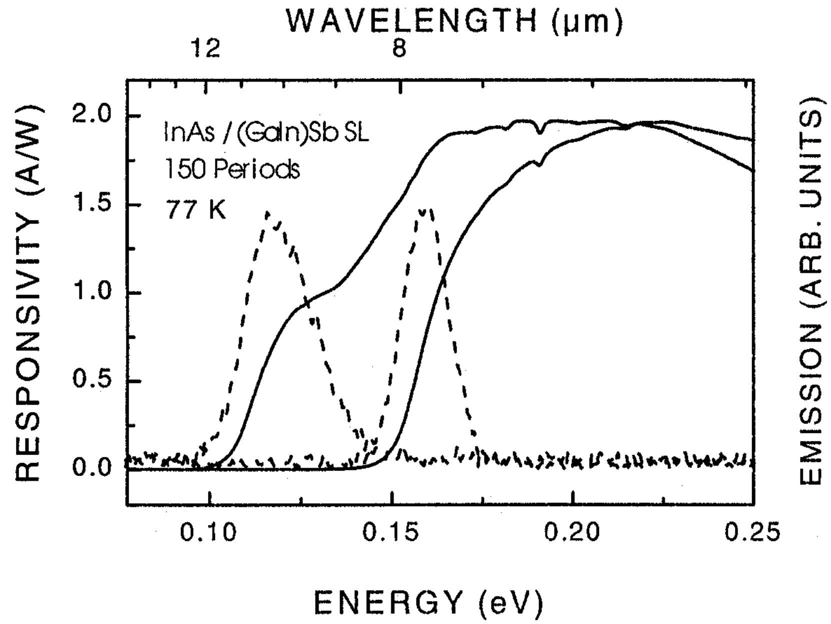
- **High temperature dark current is diffusion limited, low temperature is trap assisted tunneling limited**
- **RoA(80K)=40 Ω-cm^2**
    - **D*=1.4x10^{11} (50% BLIP at f/2)**

- **Elimination of defect related tunneling mechanism would result in high RoAs (7000) at 80 K**
    - **D*= 2x10^{12} (BLIP at low backgrounds)**

Current State of the Art - GaInSb/InAs Superlattice IR Detectors

• Fuchs et. al. Fraunhofer Inst.

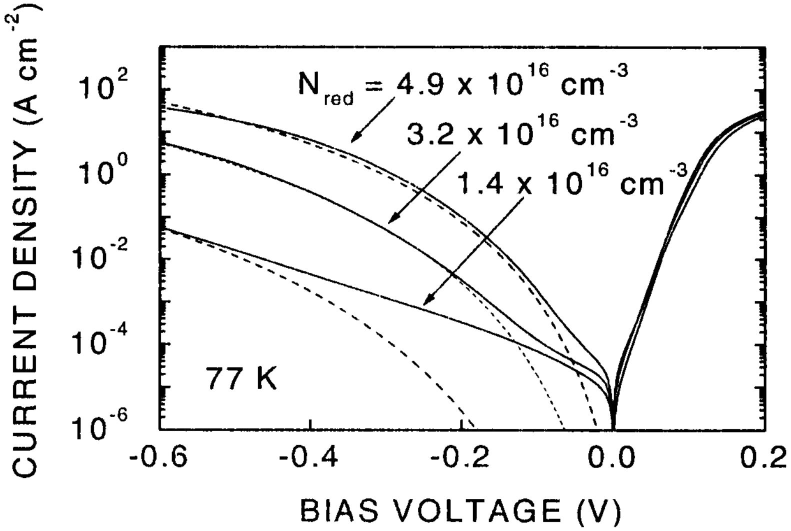


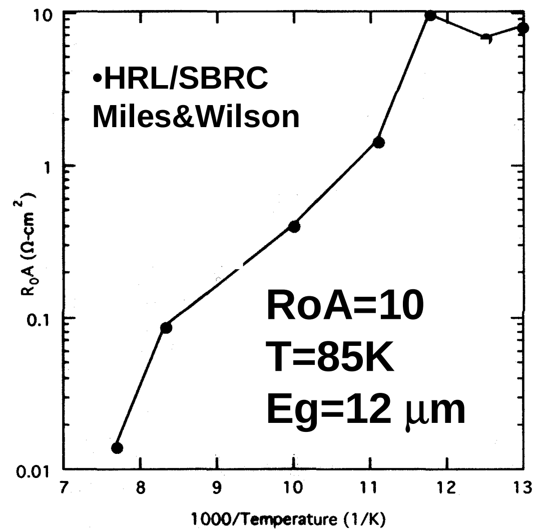


- RoA 'comparable' to HgCdTe
- D* calculated based on RoA Johnson noise limit (no noise measurement reported)
- Activation energy doesn't agree with optical gap
- Individual device results

- Good agreement with theory predictions for responsivity (absorption coefficient)
- Relatively soft absorption edge and lower than optimum responsivity because of material thickness

Current State of the Art - GaInSb/InAs Superlattice IR Detectors cont.



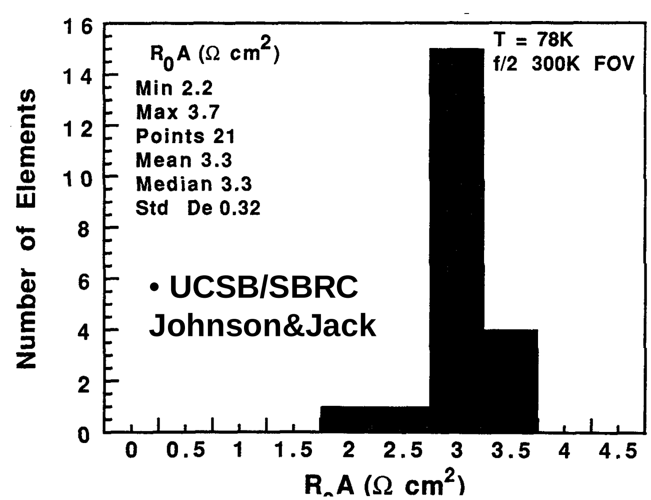


- Devices are 'tunneling' limited for reverse biases required for operation in a typical focal plane
    - RoA is not sufficient metric for FPA performance

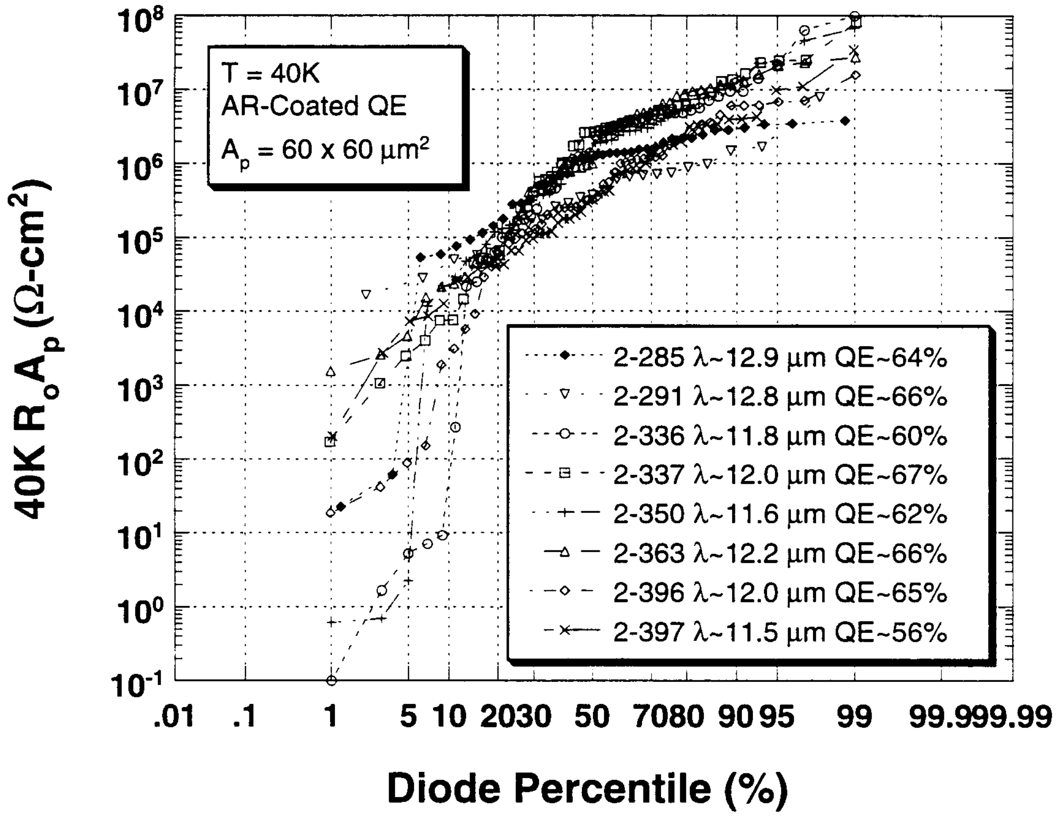
- Individual devices suggest technology potential, but detailed performance on array #s not demonstrated

•"Best" reported RoA/Top/Eg combination

• Responsivity / QE/ λc????



High Performance Low Background HgCdTe at Wavelengths Beyond 12 Microns



- **Many detectors in an array meet performance requirements for low background operation, a statistically significant fraction suffer from degraded performance associated with defect and tunneling related phenomena.**

IR Detector Related Material System Research Issues

- Validation of Auger lifetimes at low carrier densities
- Elimination of defect related dark currents
    - Tunneling, SRH generation
- Strain effects in thick (5 micron) layers
- Extension to longer cutoff wavelengths
- Substrate quality
- Growth on compliant substrates
- Compositional uniformity over large areas
- Elimination of ‘macroscopic’ defects
- Surface passivation
- Multispectral capability